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THERMAL ANALYSIS OF AN IRRADIATED FUEL CONCRETE INTEGRATED CONTAINER UNDER NORMAL AND FIRE ACCIDENT CONDITIONS

Report No 89-242-K

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Engineer
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ABSTRACT

A three-dimensional heat transfer code has been developed for the thermal analysis of a Concrete Integrated Container (CIC) for the transportation of 10 year cooled fuel under normal conditions and hypothetical fire accident conditions. The code is based on the numerical solution of the conservation equations of mass ,momentum and energy. The temperature distribution within the cask cavity was obtained by modelling the cavity as two separate regions. The region occupied by the four fuel modules was represented by a porous medium. The remainder of the cavity was modelled as a pure fluid region. Previous work (half-scale CIC cavity experimental results /4/) has shown good comparison with present code predictions for heat input levels in the range of 0.25 to 5 W/bundle (2 to 40 W/bundle in full-scale). Analytical results for the full-scale CIC are also presented for 10 year cooled fuel (6 W/Bundle /10/). The final design calculations for licensing purposes will be presented in other reports using the present computer code.

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This report presents the special purpose three-dimensional heat transfer computer code for the thermal analysis of a Concrete Integrated Container (CIC) under normal and fire accident conditions. The results of this work include:

1. Comparisons of theoretical predictions with existing half-scale CIC experimental results.

2. Representative analytical results for full-scale CIC under normal and fire accident conditions.

The results of this study provide the necessary confidence in the 3-D code to perform the final design calculations for the transportation of 10 year cooled fuel under normal and hypothetical fire accident conditions.

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LIST OF SYMBOLS

Subscripts

i, j, k	denotes conditions at a grid point
e	denotes effective properties
f	denotes fluid properties
W	denotes conditions at a wall

Superscripts

n	denotes conditions at a time step

Variables

a	thermal diffusivity, m^2/s
c	specific heat, $J/(kg \cdot °C)$
g	acceleration due to gravity, m^2/s
h_F	heat transfer coefficient from fire, $W/(m^2 \cdot °C)$
h_H	heat transfer coefficient for horizontal surface, $W/(m^2 \cdot °C)$
h_V	heat transfer coefficient for vertical surface, $W/(m^2 \cdot °C)$
K	flow conductivity, m^2
P	pressure, (kPa)a
$\dot{q}_H$	insolation for horizontal surface, W/m^2
$\dot{q}_S$	heat flux at outer surface, W/m^2
$\dot{q}_V$	insolation for vertical surface, W/m^2
$\dot{q}_W$	heat flux at inner surface, W/m^2
$\dot{Q}_G$	heat generation, W/m^3

$\dot{Q}_R$	radiant heat exchange within fuel region, W/m^3
t	time, s
T	temperature field, °C
T_A	ambient temperature, °C
T_{AC}	average temperature of adjacent finite difference cells, °C
T_{AF}	average fuel temperature, °C
T_{AFS}	average fuel surface temperature, °C
T_{CF}	average cavity fluid temperature, °C
T_{EW}	average external wall temperature, °C
T_{FL}	flame temperature, °C
T_{IL}	inner lid temperature (center), °C
T_{IW}	average internal wall temperature, °C
T_{MF}	maximum fuel sheath temperature, °C
T_{MC}	maximum outer surface (center) temperature, °C
T_{MS}	maximum outer surface temperature, °C
T_{MW}	maximum inner surface temperature, °C
T_{OL}	outer lid temperature, °C
T_r	reference temperature, °C
T_S	outer surface temperature, °C

T_W	inner surface temperature, °C
x,y,z	coordinate system, m
$\vec{V}$	velocity field, m/s

Greek Symbols

α_S	outer surface absorptivity
β	coefficient of volume expansion, 1/°C
ΔS	surface area of a finite difference cell, m^2
Δt	time step, s
ΔV	volume of a finite difference cell, m^3
ε	effective emissivity
ε_E	outer surface emissivity
ε_F	fuel region emissivity
ε_{FL}	flame emissivity
ε_I	inner surface emissivity
λ	thermal conductivity, W/(m.°C)
ν	kinematic viscosity, m/s^2
ρ	density, kg/m^3
σ	Steffan Boltzman constant, $W/(m^2.°K^4)$
ϕ	fuel region porosity

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8. Summary of Results - Fire

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To Mr. P.D. Stevens-Guille
Nuclear Engineering
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THERMAL ANALYSIS OF AN IRRADIATED FUEL CONCRETE INTEGRATED CONTAINER UNDER NORMAL AND FIRE ACCIDENT CONDITIONS

1.0 INTRODUCTION

A special purpose 3-D heat transfer code has been developed for the thermal analysis of the Concrete Integrated Container (CIC) for 10 year cooled fuel. In addition to the velocity field within the cavity, the code provides the temperature distribution throughout the entire container. This data is required for evaluating the performance of the CIC for transporting 10 year cooled fuel under normal and fire accident conditions as specified in the Regulations/1/. The main objectives of this report are to describe the following:

a) Development of the CIC heat transfer code

b) Verification of the CIC heat transfer code using existing experimental results/4/

The application of the code is demonstrated through the analysis of a full-scale CIC under normal and fire accident conditions. The final design calculations which will assist the Nuclear Engineering Department to produce a safety analysis report for AECB licensing purposes will be presented in other reports.

2.0 DEVELOPMENT OF THE CIC HEAT TRANSFER CODE

Figure 1 shows the CIC in the horizontal orientation. The container is of rectangular geometry with a cavity accommodating 4 fuel modules. One such a module is shown in Figure 2. It consists of 48 tubes with each tube accommodating 2 fuel bundles. A maximum of 384 fuel bundles can be stored in the CIC cavity. The CIC inner and outer liners are made of carbon steel and the

space between the liners is filled with high density concrete.

The heat generated within the CIC cavity is transferred to the inner surfaces by natural convection, conduction and radiation and is then conducted through the container walls. Thermal exchange with the environment to/from the outer surface is by natural convection and radiation. In developing the analytical tools the following assumptions have been made:

2.1 Assumptions

CIC Wall:

a) Thermal properties are independent of temperature.

b) Before and after the fire the CIC is considered to be in a black environment (thermal radiation emitted from the CIC outer surface is absorbed by the surrounding).

c) Heat transfer through the impact limiters (considered only during normal operation of the CIC) is negligible. For the fire accident scenarios these impact limiters were not considered necessary.

CIC Cavity:

a) Flow is incompressible and laminar.

b) Thermal properties are uniform throughout the cavity (except density changes)

c) Fuel region is represented by a porous medium based on the experimental results of Reference /5/.

It should be noted that fluid properties were evaluated at the bulk fluid temperature.

2.2 Governing Equations

Based on the above assumptions the equations governing the heat flow throughout the CIC are as follow:

CIC Wall:

The heat transfer through the wall is given by:

$$\rho c \frac{\partial T}{\partial t} = \lambda \nabla^2 T$$

CIC Cavity:

The CIC cavity is modelled by separating it into two regions, a fluid region and a porous region. The fluid region consists of the cavity portion that contains fluid only. The porous region consists of the fuel modules containing the fuel bundles and the fluid occupying the void spaces. The fluid transfers the heat by conduction and convection to the walls of the CIC. The effects of the radiant heat exchange within the fuel module tubes as well as the radiant heat excange between the fuel region and the inner walls of the CIC were also modelled.

a) Fluid Region

The equations governing the fluid region are:

$$\nabla . \vec{V} = 0$$

$$\frac{D\vec{V}}{Dt} = - \frac{1}{\rho} \nabla P - \vec{g}\beta(T - T_r) + \nu \nabla^2 \vec{V}$$

$$\rho c \frac{DT}{Dt} = \lambda \nabla^2 T$$

b) Porous Region

The equations governing the porous region are:

$$\nabla . \vec{V} = 0$$

$$\frac{1}{\phi} \frac{D\vec{V}}{Dt} = - \frac{1}{\rho} \nabla P - \frac{\nu}{K} \vec{V} - \vec{g}\beta(T - T_r)$$

$$(\rho c)_e \frac{\partial T}{\partial t} + (\rho c)_f \nabla . (\vec{V} T) = \lambda_e \nabla^2 T + \dot{Q}_G - \dot{Q}_R$$

where:

$$\dot{Q}_R = \sigma \varepsilon_F \frac{\Delta S}{\Delta V} (T^4 - T_{AC}^4)$$

The above equations have been numerically solved using the MAC (Marker And Cell) method. The finite difference approximations to these equations and the solution procedure have been described elswhere /5,6,7,8/.

For a cavity containing air the internal pressure is obtained from the ideal gas equation of state using the bulk fluid temperature.

The CIC heat transfer code has been developed for the thermal analysis of the full-scale CIC. The code provides average temperatures for the module tube-fuel bundle assemblies but does not explicitly give the fuel sheath temperature. As described in Reference /2/ the maximum fuel sheath temperature was determined from previous experimental results.

3.0 VERIFICATION OF THE CIC HEAT TRANSFER CODE

The verification of the code has been carried out for the cavity model only. This involves testing the adequacy of the code to predict the temperature distribution within the CIC cavity. The verification of the computer model for the heat input from the fire to the CIC surface and also for the conduction through the wall has been previously accomplished /2/. Therefore only the verification of the heat transfer model for the cavity is described below.

The theoretical cavity model was verified using half-scale experimental results/4/. Figure 3 shows the dimensions for the theoretical model of the cavity. Table 1 lists the thermal properties of the fluid and fuel region used in the analysis. The following initial and boundary conditions were applied:

Initial Conditions:

at t=0: $\vec{V}=0$; P=1 ; $T=T_A$

Boundary Conditions:

$\vec{V}_W=0$; $T=T_W$

Using the code and the experimental wall temperatures (Figure 4 and Table 1) as boundary conditions, temperature distributions within the cavity containing air have been obtained for various heat inputs. Figure 5 compares the theoretical average temperature of the hottest module tube/bundle assembly with the experimental results of reference /4/. As this figure illustrates the theoretical predictions are in good agreement with the experimental results.

4.0 APPLICATION OF THE CIC HEAT TRANSFER CODE

The main purpose of this section is to demonstrate the application of the code for a full-scale CIC under normal and fire accident conditions. The final design calculations for licensing purposes will be presented in other reports.

The heat transfer code (CIC-NF) for the analysis of full-scale CIC under normal and fire accident conditions is listed in Appendix A.

4.1 Thermal Analysis-Normal

To determine the maximum wall and fuel temperatures for a four-module CIC during normal operation, the following initial and boundary conditions have been applied:

Initial Conditions:

at $t=0$; $\vec{V}=0$; $P=1$; $T=T_A$

Boundary Conditions:

i) Outer Surface

This boundary condition includes the heat loss by convection and radiation and also the insolation gain.

$$\dot{q}_S = \begin{cases} h_H(T_A - T_S) + \sigma\varepsilon_E(T_A^4 - T_S^4) + \dot{q}_H & \text{for horizontal surfaces} \\ h_V(T_A - T_S) + \sigma\varepsilon_E(T_A^4 - T_S^4) + \dot{q}_V & \text{for vertical surfaces} \end{cases}$$

Where h_H and h_V are evaluated from correlations of natural convection/2/.

ii) Inner Surface

$\vec{V}_W = 0$

$q_W = \lambda_e \frac{\partial T}{\partial n} + \sigma \varepsilon_I (T_{AFS}^4 - T_W^4)$

where:

$\frac{\partial T}{\partial n}$ = temperature gradient normal to the surface

The analysis under normal conditions is accomplished by incorporating the above initial and boundary conditions into the code. This code computes the natural convection including the heat conduction through the fuel region and radiant heat exchange within the cavity. It further computes the heat conduction through the wall by accounting for the heat loss (by natural convection and radiation) and the insolation gain (solar heating). For insulated surfaces (impact limiters and bottom of CIC) the heat flux is set equal to zero. The required data for this analysis are presented in Figure 6 and Tables 3 and 4.

The main results obtained at locations of interest are summarized in Table 5. These results correspond to zero insolation gain and also to insolation gain for 12 hours.

4.2 Thermal Analysis-Fire

The thermal response of the CIC to an 800 °C engulfing fire of 0.5 hour duration was carried out by applying the following initial and boundary conditions to the governing equations.

Initial Conditions:

at t=0 ; $\vec{V}$, P and T results from normal analysis with insolation.

Boundary Conditions:

i) Outer Surface

Assuming that during the fire the heat input to the CIC outer surface is by natural convection and radiation, the following boundary conditions apply:

During the fire

$$\dot{q}_S = h_F(T_{FL} - T_S) + \sigma\varepsilon (T_{FL}^4 - T_S^4) \text{ for all surfaces } (h_F/1/)$$

where:

$$\varepsilon = (1/\varepsilon_{FL} + 1/\alpha_S - 1)^{-1}$$

After the fire, the boundary conditions given below apply. It includes the heat loss by natural convection and radiation as well as the insolation gain.

After the fire

$$\dot{q}_S = \begin{cases} h_H(T_A - T_S) + \sigma\varepsilon_E(T_A^4 - T_S^4) + \dot{q}_H & \text{for horizontal surfaces} \\ h_V(T_A - T_S) + \sigma\varepsilon_E(T_A^4 - T_S^4) + \dot{q}_V & \text{for vertical surfaces} \end{cases}$$

In the post fire analysis, the heat loss from the bottom of the CIC was ignored.

ii) Inner Surface

$$\vec{V}_W = 0$$

$$\dot{q}_W = \lambda_e \frac{\partial T}{\partial n} + \sigma\varepsilon_I (T_{AFS}^4 - T_W^4)$$

where:

$\frac{\partial T}{\partial n}$ = temperature gradient normal to the surface

The analysis was carried out based on the information given in Figure 7 and Tables 6 and 7. The above initial and boundary conditions take care of the requirements for the analysis during fire accident conditions. The post fire (cooldown) analysis was performed using initial conditions from the results of the 0.5 hour fire analysis.

Figure 8 shows the fire accident analysis results at several CIC locations as a function of time and Table 8 summarizes the maximum temperatures attained under fire accident conditions. These results correspond to alternating 12 hours insolation for a period of 60 hours after the fire. At that time all temperatures throughout the container have reached their maximum value and have begun to decline.

5.0 CONCLUSIONS

a) The verification of the code has been accomplished by comparing the predicted temperatures with the experimental results of reference /4/. As can be seen from Figure 5 the predicted temperature for the hottest module tube as a function of the decay heat level is in close agreement with the measurements.

b) During normal operation of the full-scale CIC (with 2 impact limiters and insolation gain) for 10 year cooled fuel (6 W/bundle) the average external wall temperature will be 90.4 °C. The fuel sheath temperature will reach a maximum value of 141.1 °C. The corresponding average cavity fluid temperature will be 126.5 °C which will result in internal pressure of 137.5 (kPa)a.

c) Under fire accident conditions the external wall temperature will reach a maximum of 771.1 °C at the end of the 800 °C half-hour fire with cavity fluid temperature of 126.5 °C.

d) During the cooling period (impact limiters off and insolation gain on) the fuel sheath temperature will reach a maximum value of 168.9 °C. With the average cavity fluid temperature reaching 156.5 °C the corresponding internal pressure will be 148.0 (kPa)a.

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REFERENCES

1. Transport Packaging of Radioactive Materials Regulations, SOR/83-740, September 29,1983.

2. Taralis, D., "Thermal Analysis for the Design of an Irradiated Fuel Transportation Cask under Normal Operating Conditions", Ontario Hydro Research Division Report No 83-221-K, May 27,1983.

3. Taralis, D., "Thermal Analysis of an Irradiated-Fuel Road Cask. Part I", Ontario Hydro Research Division Report No 85-240-K, February 1986.

4. Taralis, D., et al "Thermal Testing of a Half-Scale Concrete Integrated Container Cavity ", Ontario Hydro Research Division Report No 89-241-K, September 15 1989.

5. Butterworth, D., "The Development of a Model for Three-Dimensional Flow in Tube Bundles, "Int J Heat Mass Transfer, Vol 21, pp 253-256, 1978.

6. Roach, P.J.,"Computational Fluid Dynamics", Hermosa Publishers,1976.

7. Hirt, C.W., Nichols, B.d. and Romero, N.C., "SOLA - A Numerical Solution Algorithm for Transient Fluid Flows", Los Alamos Scientific Laboratory of the University of California, Los Alamos, New Mexico, January 1975.

8. Chan, A.M.C. and Banerjee, S., "Three-Dimensional Numerical Analysis of Transient Natural Convection in Rectangular Enclosures", ASME Journal of Heat Transfer, Vol 101, pp 114-119, February 1979.

9. Computer Listing for the Thermal Analysis of a Full-Scale CIC Under Normal and Fire Accident Conditions, File 825.122(P) October 1989.

10. McKean, D., "Shielding Analysis of the CIC", Memorandum to R.N. Sumar, File : 967-TRAN-03200-04-P, Dated February 24, 1989.

APPENDIX A

COMPUTER CODE CIC-NF

This Appendix presents the listing of the main routine of the computer code CIC-NF. The remaining 30 subroutines associated with this code are not presented, but can be found in Refererce/9/. The code has been employed to carry out the thermal analysis of a full-scale CIC for 10 year cooled fuel under normal operation and fire accident conditions.

```
C     MAIN FOR HORIZONTAL CIC-NF
      COMMON /BL1/ DX,DY,DZ,DXFA,DYFA,DZFA
      COMMON /BL2/ R,B,VK,THD,CP
      COMMON /BL3/ CR,ETD
      COMMON /BL4/ DT
      COMMON /BL5/ T1,T2,T3,T4,T5,T6
      COMMON /BL6/ M,N,L
      COMMON /BL7/ MM1,NM1,LM1,MM2,NM2,LM2
      COMMON /BL8/ TR,G
      COMMON /BL9/ ND
      COMMON /BL10/ I,J,K
      COMMON /BL11/ A11,A12,A13,X33,XM323,XP323,XM23,XP23
      COMMON /BL12/ A11M,A12M,A13M,X33M,XM323M,XP323M,XM23M,XP23M
      COMMON /BL21/ B11,B12,B13,Y33,YM323,YP323,YM23,YP23
      COMMON /BL22/ B11N,B12N,B13N,Y33N,YM323N,YP323N,YM23N,YP23N
      COMMON /BL31/ C11,C12,C13,Z33,ZM323,ZP323,ZM23,ZP23
      COMMON /BL32/ C11L,C12L,C13L,Z33L,ZM323L,ZP323L,ZM23L,ZP23L
      COMMON /BL51/ FKU,FKV,FKW
      COMMON /BL52/ SPD
      COMMON /BL53/ TDIA
      COMMON /BL54/ RD1,RD2,RD3,RD4
      COMMON /BL55/ CST1,CST2,CST3,CST4
      COMMON /BL56/ EX2,EX3,EX4
      COMMON /BL57/ UC,VC,WC
      COMMON /BL58/ IS,IE,JS,JE,KS,KE
      COMMON /BL59/ TOL,CRT,ITM,NGP,ITER
      COMMON /BL60/ IFU,IFV,IFW,IFT
      COMMON /BL61/ EPR
      COMMON /BL83/ SIG,TABS
      COMMON /BL84/ EBB,EBW,EWB
      COMMON /BL85/ M1,M2,N1,N2,K1,K2
      COMMON /BL87/ AFT1,AFT3,AFT4,AFT5
      COMMON /BL88/ ESA
      COMMON /BL89/ A1,A2
      COMMON /BL91/ RL1,RL2,RL3,RL4,RL5
      COMMON /BL92/ RU1,RU2,RU3,RU4,RU5
      COMMON /BL93/ RYT,RYB,RYL
      COMMON /BL94/ FVEL
      COMMON /BL95/ NWU
      COMMON /BLS/ S1,S2,S3,S4,S5,S6
      COMMON /BNF/ ITA
      COMMON /PRTS/ RA,TKAB,VISS,VISH,BET,CPA,GRV
      COMMON /BET/ AET1,AET3,AET4,AET5
      COMMON /BIT/ AIT1,AIT3,AIT4,AIT5
      COMMON /BSF/ AET,AIT,AFT
      COMMON /RBW/ IBB,IBW
      COMMON /CND1/ YZ,XZ,XY,YZDX,XZDY,XYDZ
      COMMON /CND2/ TC1,TC2,TC3,TC4,TC5,TC6,TC7,TC8
      COMMON /CND3/ E,TF,TA,QHI,QVI,HTP,HBP,HLP
      COMMON /CND4/ TF1,TF2,TF3,TF4,TF5,TF6
      COMMON /CND5/ ICF
      COMMON /CND6/ ILD
      COMMON /CND9/ IO,MCI,NCI,LCI
      COMMON /CND11/ ILZ
      COMMON /CND12/ CQ,CL
      DIMENSION A(4,5,9,9)
      DIMENSION U(5,9,9),V(5,9,9),W(5,9,9),P(5,9,9),T(5,9,9)
      DIMENSION Q(5,9,9),NCP(5,9,9),DFDP(5,9,9)
      DIMENSION QR(5,9,9)
      DIMENSION NCR(5,9,9)
      DIMENSION T1(25,25),T2(25,25),T3(25,25)
      DIMENSION T4(25,25),T5(25,25),T6(25,25)
      DIMENSION TF1(25,25),TF2(25,25),TF3(25,25)
      DIMENSION TF4(25,25),TF5(25,25),TF6(25,25)
      DIMENSION CQ(6,25,25),CL(6,25,25)
      DIMENSION DX(50),DY(50),DZ(50),DXFA(50),DYFA(50),DZFA(50)
      DIMENSION XX(50),YY(50),ZZ(50)
      DIMENSION DFDP1(50),DFDP2(50),DFDP3(50)
      DIMENSION C(2,7,14,11)
      DIMENSION NCC(7,14,11)
      DIMENSION NFL(7,14,11)
      DIMENSION FXC(7,14,11),FXR(7,14,11)
C
C     DATA FOR SELECTING N (ITA=1) / F (ITA=2)
      DATA ITA/1/
      DATA INS/1/
C
C     DATA FOR RADIATIVE HEAT TRANSFER
```

```
C
      DATA IRF,IBB,IBM/1,1,1/
      DATA EW,EB/0.5,0.7/
      DATA A1,A2/3.3745,3.5945/
      DATA F12,F21/1.0,0.9388/
C
C     DATA FOR CONVECTIVE HEAT TRANSFER
C
      DATA (DX(I),I=1,5)/5*0.1758/
      DATA (DY(J),J=1,9)/9*0.1860/
      DATA (DZ(K),K=1,9)/9*0.1754/
      DATA M,N,L/5,9,9/
      DATA M1,M2,N1,N2,K1,K2/2,4,2,8,2,8/
      DATA R,CP,TK,VK,B/0.96,1009.0,0.03,2.22E-5,2.736E-3/
      DATA RS,CPS,TKS/10500.0,280.0,0.03/
      DATA TR/38.0/
      DATA CST1,CST2,CST3,CST4/9.0E-4,1.3022E-3,8.5467E-3,34.93E-3/
      DATA EX2,EX3,EX4/0.1605,0.62,0.8858/
      DATA IBC/2/
      DATA DT/0.2/
      DATA ND/3/
      DATA QU/751.7/
      DATA EPR/0.51/
      DATA NS,NTS/35999,500/
      DATA NCOUNT,NW/0,1/
      DATA ITM/100/
      DATA TOL/1.0E-4/
      DATA SPD/1.7/
      DATA G/9.81/
      DATA TDIA/0.1/
      DATA RD1,RD2,RD3,RD4/1.0E1,6.0E1,2.0E2,1.0E4/
      DATA UC,VC,WC/3*0.0/
      DATA NPF,NPM/1,2/
      DATA NRED/1/
      DATA NCAV/1/
      DATA NWAL/1/
      DATA TCAVI/70.41/
      DATA ET1,ET2,ET3,ET4,ET5,ET6/6*70.41/
      DATA IET/0/
C
C     DATA FOR HEAT CONDUCTION
C
      DATA SIG,TABS/5.669E-8,273.0/
      DATA MC,NC,LC/7,14,11/
      DATA MCI,NCI,LCI/7,11,11/
      DATA IO/4/
      DATA DXC,DYC,DZC/0.1758,0.1860,0.1754/
      DATA TKC,RC,CPC/2.77,3500.0,838.0/
      DATA TKF/0.4482/
      DATA DTC/100.0/
      DATA NSC,NTC/71,432/
      DATA TA,TF/38.0,800.0/
      DATA QVI,QHI/200.0,800.0/
      DATA EF,EA/0.9,0.8/
      DATA ESA/0.5/
      DATA FVEL/10.0/
      DATA ICF/1/
      DATA ILD/0/
      DATA STP,SBP,SLP/2.11,2.11,2.418/
      DATA APL/1.1372/
      DATA TWALI/60.5/
      DATA ILZ/5/
      DATA NWU/9/
C
      OPEN(5,FILE='IN.DAT',STATUS='OLD')
      OPEN(6,FILE='OUT.DAT',STATUS='NEW')
      OPEN(9,FILE='SAV.DAT',STATUS='NEW')
      OPEN(10,FILE='STR.DAT',STATUS='NEW')
      OPEN(15,FILE='CHK.DAT',STATUS='NEW')
      OPEN(16,FILE='ERC.DAT',STATUS='NEW')
C
C     EVALUATION OF CONSTANTS FOR HEAT CONDUCTION
C
      MM1=M-1
      NM1=N-1
      LM1=L-1
      MM2=M-2
      NM2=N-2
```

```
      LM2=L-2
      X=DXC/2.0
      Y=DYC/2.0
      Z=DZC/2.0
      YZ=Y*Z
      XZ=X*Z
      XY=X*Y
      XYZ=X*Y*Z
      YZDX=YZ/DXC
      XZDY=XZ/DYC
      XYDZ=XY/DZC
      TC=RC*CPC*XYZ
      TC1=TC
      TC2=2.0*TC
      TC3=3.0*TC
      TC4=4.0*TC
      TC5=5.0*TC
      TC6=6.0*TC
      TC7=7.0*TC
      TC8=8.0*TC
      DO 91 K=1,LC
      DO 91 J=1,MC
      DO 91 I=1,MC
      C(1,I,J,K)=TWALI
   91 CONTINUE
C
C     EVALUATION OF CONSTANTS FOR CONVECTION
C
      THD=TK/(R*CP)
      CF=R*CP
      CS=RS*CPS
      ETK=EPR*TK+(1.0-EPR)*TKS
      EHC=EPR*CF+(1.0-EPR)*CS
      ETD=ETK/EHC
      CR=CF/EHC
      DO 4 I=2,MM1
      DXFA(I-1)=(DX(I-1)+DX(I))/2.0
      DXFA(I)=(DX(I)+DX(I+1))/2.0
      IF(I.EQ.2) XX(I-1)=-DX(I-1)/2.0
      XX(I)=XX(I-1)+DXFA(I-1)
      DFDP1(I)=(1.0/DXFA(I-1)+1.0/DXFA(I))/DX(I)
    4 CONTINUE
      DO 5 J=2,MM1
      DYFA(J-1)=(DY(J-1)+DY(J))/2.0
      DYFA(J)=(DY(J)+DY(J+1))/2.0
      IF(J.EQ.2) YY(J-1)=-DY(J-1)/2.0
      YY(J)=YY(J-1)+DYFA(J-1)
      DFDP2(J)=(1.0/DYFA(J-1)+1.0/DYFA(J))/DY(J)
    5 CONTINUE
      DO 6 K=2,LM1
      DZFA(K-1)=(DZ(K-1)+DZ(K))/2.0
      DZFA(K)=(DZ(K)+DZ(K+1))/2.0
      IF(K.EQ.2) ZZ(K-1)=-DZ(K-1)/2.0
      ZZ(K)=ZZ(K-1)+DZFA(K-1)
      DFDP3(K)=(1.0/DZFA(K-1)+1.0/DZFA(K))/DZ(K)
    6 CONTINUE
      NGP=MM2*MM2*LM2
      GRF=0.0
      PRL=VK/THD
      RAH=GRF*PRL
      IF(IBC.EQ.1) CALL TCS1
      IF(IBC.EQ.2) CALL TCS2
C
C     INITIALIZATION OF VARIABLES
C
      DO 10 K=1,L
      DO 10 J=1,M
      DO 10 I=1,M
      U(I,J,K)=0.0
      V(I,J,K)=0.0
      W(I,J,K)=0.0
      T(I,J,K)=TCAVI
      A(4,I,J,K)=TCAVI
      P(I,J,K)=1.0
      QR(I,J,K)=0.0
      Q(I,J,K)=0.0
      NCP(I,J,K)=NPF
   10 CONTINUE
```

```
      DO 15 K=K1,K2
      DO 15 J=M1,M2
      DO 15 I=M1,M2
      NCP(I,J,K)=NPM
      Q(I,J,K)=QU/ENC
   15 CONTINUE
      DO 42 K=1,L
      WRITE(6,31)
   31 FORMAT(/)
      DO 42 I=1,M
      WRITE(6,41) (NCP(I,J,K),J=1,N)
   41 FORMAT(25I5)
   42 CONTINUE
      EBB=1.0/(1.0/EB+1.0/EB-1.0)
      EBW=1.0/((1.0-EB)/EB+1.0/F12+(A1/A2)*((1.0-EW)/EW))
      EWB=1.0/((1.0-EW)/EW+1.0/F21-(A2/A1)*((1.0-EB)/EB))
      IF(ITA.EQ.1) E=0.0
      IF(ITA.EQ.2) E=1.0/(1.0/EF+1.0/EA-1.0)
      IF(ITA.EQ.2) ESA=0.0
      IF(ITA.EQ.2) TA=TF
      IF(INS.EQ.0) QVI=0.0
      IF(INS.EQ.0) QHI=0.0
      IF(IRF.GT.0) CALL NCRAD(NCR)
C
C     SOLUTION OF HEAT CONDUCTION
C
      TIME=0.0
      TIMC=0.0
      IF(NRED.GT.0) CALL READ(TIMC,TIME,C,U,V,W,T,P,A,MC,NC,LC)
      IF(NWAL.GT.0) CALL NLCH(NCC,NFL,MC,NC,LC)
      NCNT=0
      NMC=1
   32 CONTINUE
      NCNT=NCNT+1
      IF(NWAL.EQ.0) GO TO 125
      TSG1=(C(1,1,1,1)+C(1,1,NC,1)+C(1,1,1,LC)+C(1,1,NC,LC))/4.0
      TSG4=(C(1,1,NC,1)+C(1,1,NC,LC)+C(1,MC,NC,1)+C(1,MC,NC,LC))/4.0
      TSG5=(C(1,1,1,1)+C(1,1,NC,1)+C(1,MC,1,1)+C(1,MC,NC,1))/4.0
      TSG=(TSG1+TSG4+TSG5)/3.0
      CALL CVR(TA,TSG,STP,SBP,SLP,HTP,HBP,HLP)
      CALL FLT(A,MCI,NCI,LCI,IC)
      IF(IBW.GT.0) CALL TAVF(A)
      TIMC=TIMC+DTC
      CALL ATCW(C,A,MC,NC,LC,NGP,APL,HIS)
      IF(ITA.EQ.1) CALL CONDN(DTC,TKC,TKF,MC,NC,LC,C,NCC,NFL,FXC,FXR)
      IF(ITA.EQ.2) CALL CONDF(DTC,TKC,TKF,MC,NC,LC,C,NCC,NFL,FXC,FXR)
      IF(NCNT.NE.NMC) GO TO 120
      NMC=NMC+NSC
      IF(NCNT.EQ.1) NSC=NSC+1
      WRITE(6,172)
  172 FORMAT('1')
      WRITE(6,112) TIMC
  112 FORMAT( ' TIME=',E15.4)
  114 CONTINUE
      DO 118 K=1,LC
      WRITE(6,115)
  115 FORMAT(/)
      DO 118 J=1,MC
      JT=MC+1-J
      WRITE(6,116) (C(1,I,JT,K),I=1,MC)
  116 FORMAT(11E11.4)
  118 CONTINUE
      IF(RYT.LT.RL1.OR.RYT.GT.RU2) WRITE(6,81) RL1,RYT,RU2
      IF(RYB.LT.RL3.OR.RYB.GT.RU3) WRITE(6,82) RL3,RYB,RU3
      IF(RYL.LT.RL4.OR.RYL.GT.RU5) WRITE(6,83) RL4,RYL,RU5
   81 FORMAT(' RL1=',E12.5,2X,'RYT=',E12.5,2X,'RU2=',E12.5)
   82 FORMAT(' RL3=',E12.5,2X,'RYB=',E12.5,2X,'RU3=',E12.5)
   83 FORMAT(' RL4=',E12.5,2X,'RYL=',E12.5,2X,'RU5=',E12.5)
      WRITE(6,92) HTP,HBP,HLP,HIS
   92 FORMAT(' HTP=',E12.5,' HBP=',E12.5,' HLP=',E12.5,' HIS=',E12.5)
      WRITE(6,93) AET1,AET3,AET4,AET5
      WRITE(6,93) AIT1,AIT3,AIT4,AIT5
      WRITE(6,93) AET,AIT
   93 FORMAT(4E12.5)
      IF(ILD.EQ.1) CALL AEST(C,MC,NC,LC,ILE)
      CALL ISA(MC,NC,LC,DXC,DYC,DZC,FXC,FXR)
C      CALL WRITE(TIMC,TIME,C,U,V,W,T,P,MC,NC,LC)
  120 CONTINUE
```

```
  125 CONTINUE
C
C     INCREMENT OF TIME
C
      NECT=0
      IF(IET.GT.0) CALL EBC(ET1,ET3,ET4,ET5)
      IF(NCAV.EQ.0) GO TO 61
   11 CONTINUE
      NECT=NECT+1
      TIME=TIME+DT
C
C     CALCULATION OF VELOCITY FIELD
C
      DO 7 K=2,LM1
      DO 7 J=2,NM1
      DO 7 I=2,MM1
      CALL PMS(U,V,W)
      IFU=NCP(I,J,K)
      IFV=NCP(I,J,K)
      IFW=NCP(I,J,K)
      IF(I.LT.MM1) CALL US(A,U,V,W,P)
      IF(J.LT.NM1) CALL VS(A,U,V,W,P,T)
      IF(K.LT.LM1) CALL WS(A,U,V,W,P)
    7 CONTINUE
      CALL VBC(A)
C
C     CALCULATION OF PRESSURE FIELD
C
      DO 8 K=2,LM1
      DO 8 I=2,MM1
      DO 8 J=2,NM1
      DFDP(I,J,K)=DT*(DFDP1(I)+DFDP2(J)+DFDP3(K))
    8 CONTINUE
      CALL PS(A,P,DFDP)
      CALL VBC(A)
C
C     CALCULATION OF TEMPERATURE FIELD
C
      IF(IBW.GT.0) CALL TAVW(C,IO,MC,NC,LC,MCI,NCI,LCI)
      IF(IRF.GT.0) CALL RAD(NCR,T,QR,EHC,EIFR)
      DO 35 K=2,LM1
      DO 35 J=2,NM1
      DO 35 I=2,MM1
      IFT=NCP(I,J,K)
      CALL TS(A,U,V,W,T,Q,QR)
   35 CONTINUE
      CALL ET(C,IO,MC,NC,LC,MCI,NCI,LCI)
      IF(IBC.EQ.1) CALL TBC1(A)
      IF(IBC.EQ.2) CALL TBC2(A)
C
C     UPDATING OF VARIABLES
C
      DO 50 K=1,L
      DO 50 J=1,N
      DO 50 I=1,M
      U(I,J,K)=A(1,I,J,K)
      V(I,J,K)=A(2,I,J,K)
      W(I,J,K)=A(3,I,J,K)
      T(I,J,K)=A(4,I,J,K)
   50 CONTINUE
C
C     OUTPUT OF RESULTS
C
      NCOUNT=NCOUNT+1
      IF(NCOUNT.NE.NW) GO TO 60
      NW=NW+NS
      IF(NCOUNT.EQ.1) NS=NS+1
      WRITE(6,72)
   72 FORMAT('1')
      WRITE(6,12) TIME
   12 FORMAT(' TIME=',E15.7)
      WRITE(6,71) NCOUNT,ITER,TOL,CRT
   71 FORMAT(' NCOUNT=',I10,' ITER=',I10,' TOL=',E15.5,' CRT=',E15.5)
      WRITE(6,56) GRF,PRL,RAH
   56 FORMAT(' GRF=',E15.5,' PRL=',E15.5,' RAH=',E15.5)
      DO 55 K=2,LM1
      WRITE(6,51)
   51 FORMAT(/)
```

```
      WRITE(6,52) ZZ(K)
   52 FORMAT(' RESULTS AT PLANE Z=',E15.4,' ')
      DO 55 J=2,MM1
      WRITE(6,53) YY(J)
   53 FORMAT(' Y=',E15.4)
      DO 55 I=2,MM1
      IF(ND.GE.1) UAV=0.5*(A(1,I,J,K)+A(1,I-1,J,K))
      IF(ND.GE.2) VAV=0.5*(A(2,I,J,K)+A(2,I,J-1,K))
      IF(ND.GE.3) WAV=0.5*(A(3,I,J,K)+A(3,I,J,K-1))
      WRITE(6,54)
     'I,J,K,XX(I),UAV,VAV,WAV,A(4,I,J,K),P(I,J,K),Q(I,J,K),QR(I,J,K)
   54 FORMAT(3I5,8E14.5)
   55 CONTINUE
      WRITE(6,58) AFT
   58 FORMAT(' AFT=',E15.5)
      CALL ISA(MC,NC,LC,DXC,DYC,DZC,FXC,FXR)
      CALL WRITE(TIMC,TIME,C,U,V,W,T,P,MC,NC,LC)
   60 CONTINUE
      IF(NECT.LT.NTS) GO TO 11
   61 CONTINUE
      IF(NCNT.LT.NTC) GO TO 32
      NMU=10
      CALL PTR(A,P)
C
C     SAVE LAST TIME STEP
C
      CALL WRITE(TIMC,TIME,C,U,V,W,T,P,MC,NC,LC)
      STOP
      END
```

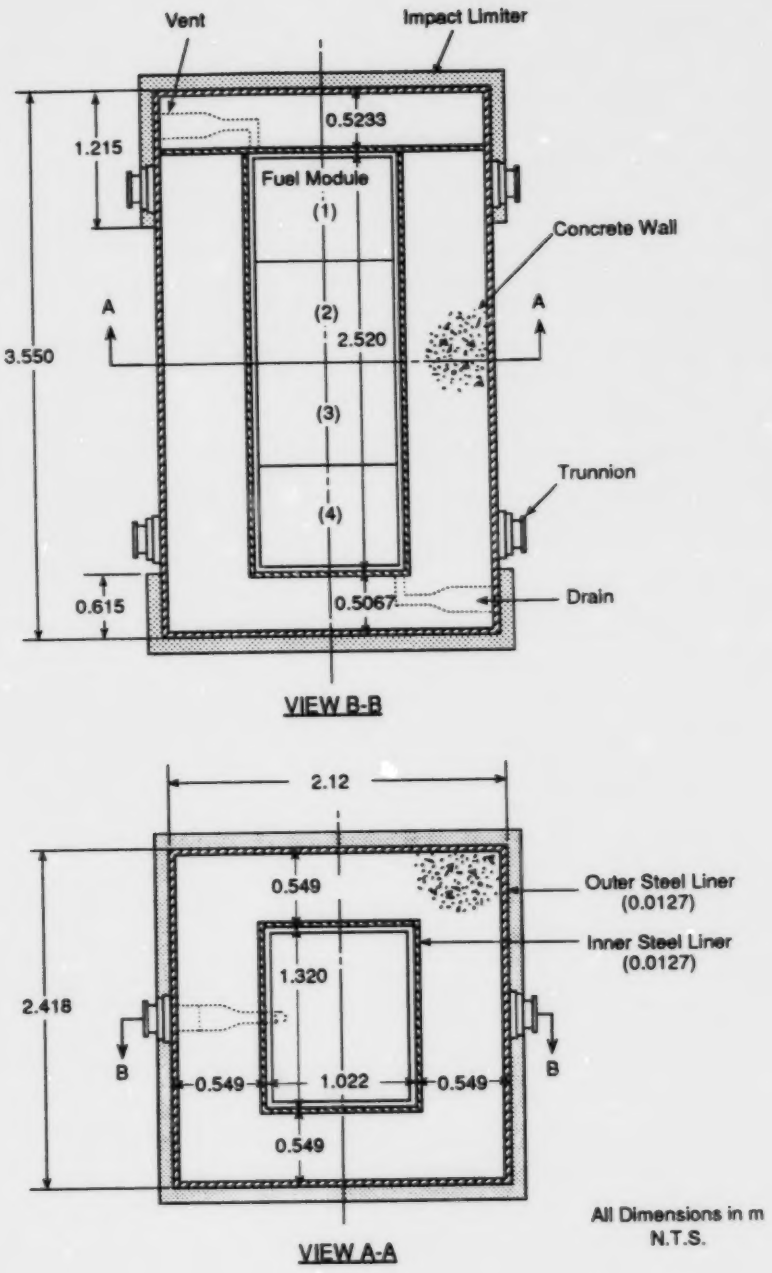


FIGURE 1

SCHEMATIC DIAGRAM OF CIC IN HORIZONTAL ORIENTATION

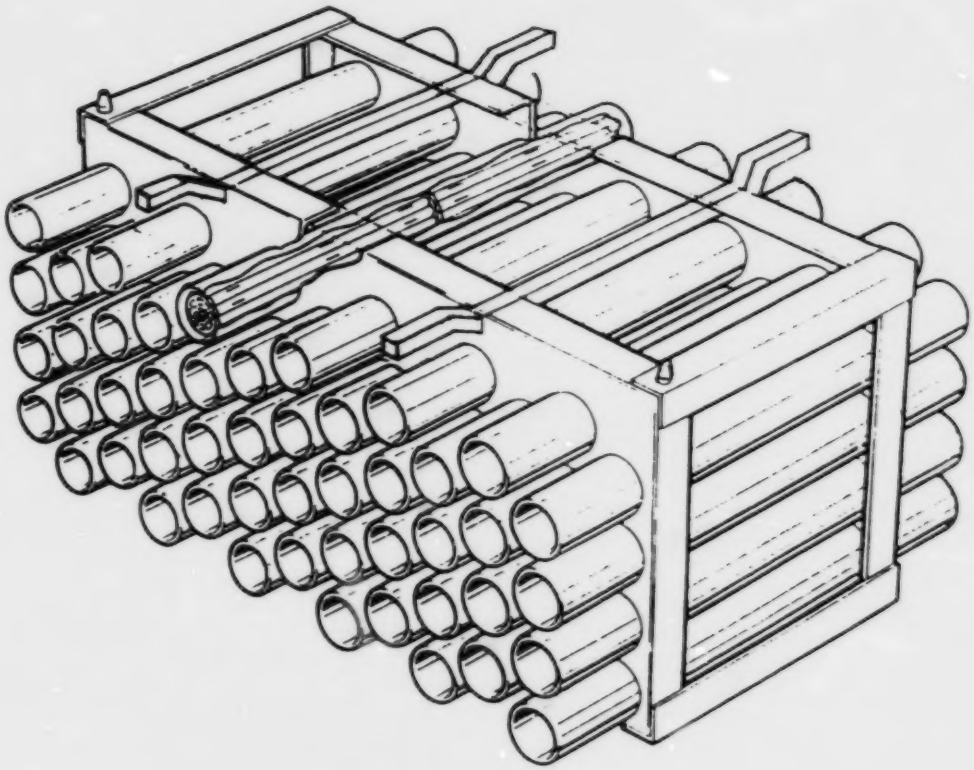
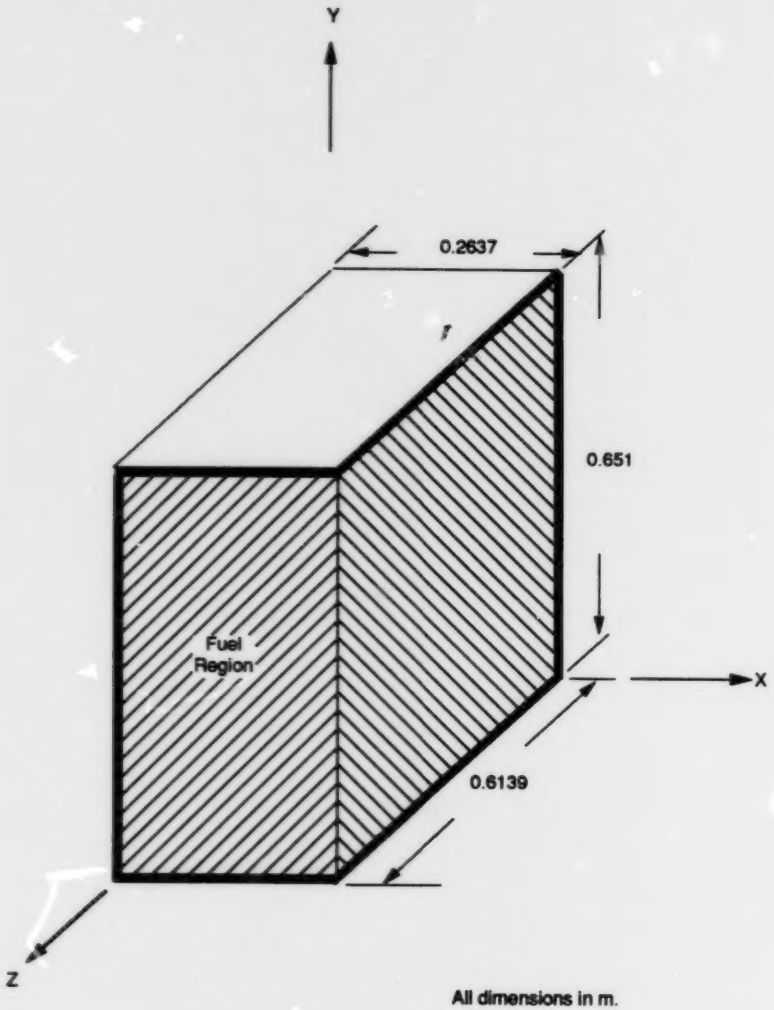


FIGURE 2

IRRADIATED FUEL STORAGE MODULE
(1.29 m x 0.99 m x 0.6 m)



All dimensions in m.

NOTE: *Due to symmetry, only 1/4 analyzed.*

FIGURE 3

DIMENSIONS FOR THEORETICAL MODEL OF EXPERIMENTAL HALF-SCALE CIC CAVITY /4/

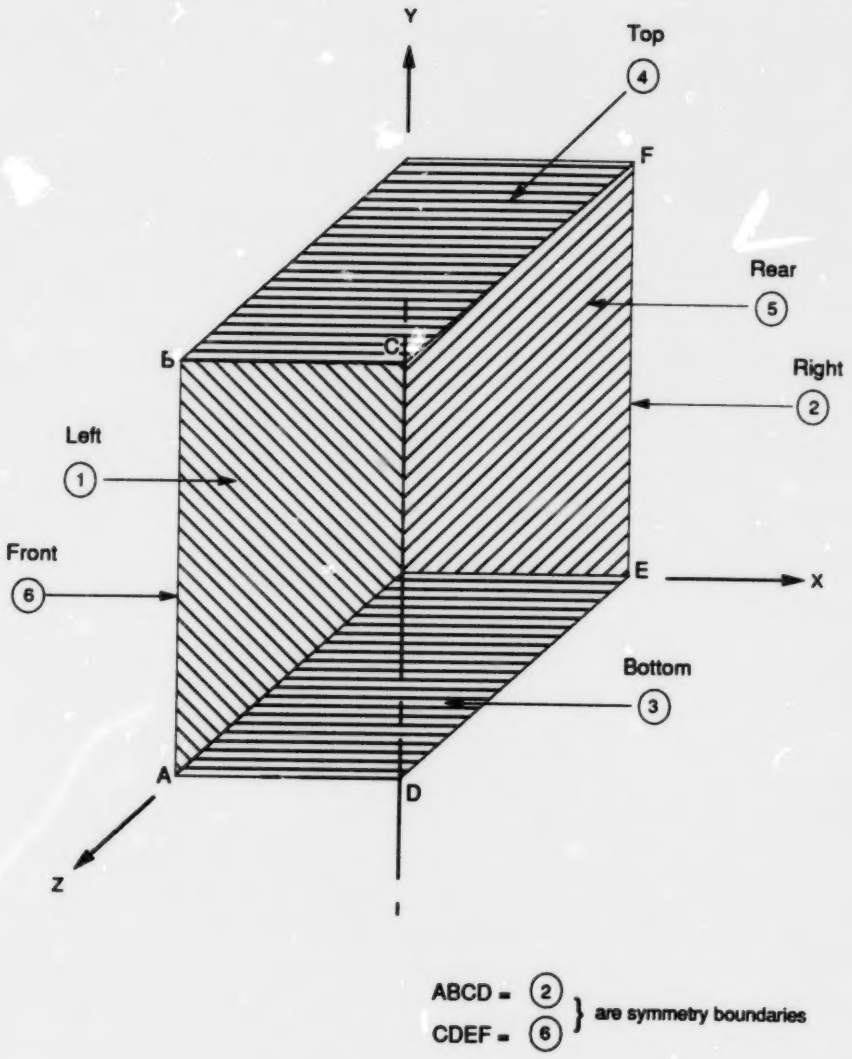


FIGURE 4

HALF-SCALE INNER WALLS WHERE EXPERIMENTAL TEMPERATURES /4/ HAVE BEEN APPLIED AS BOUNDARY CONDITIONS

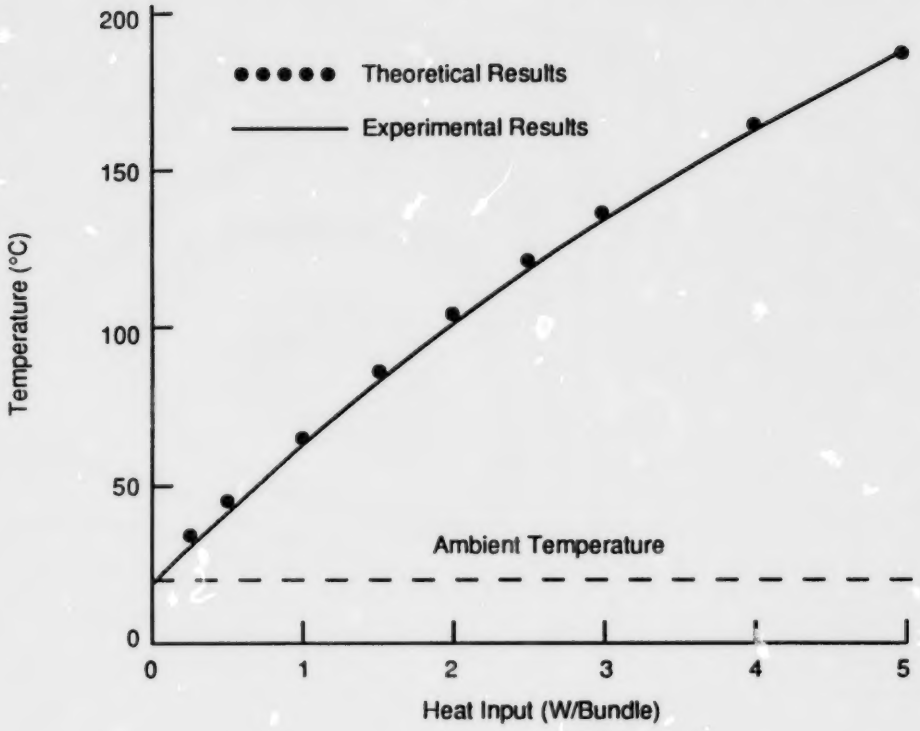
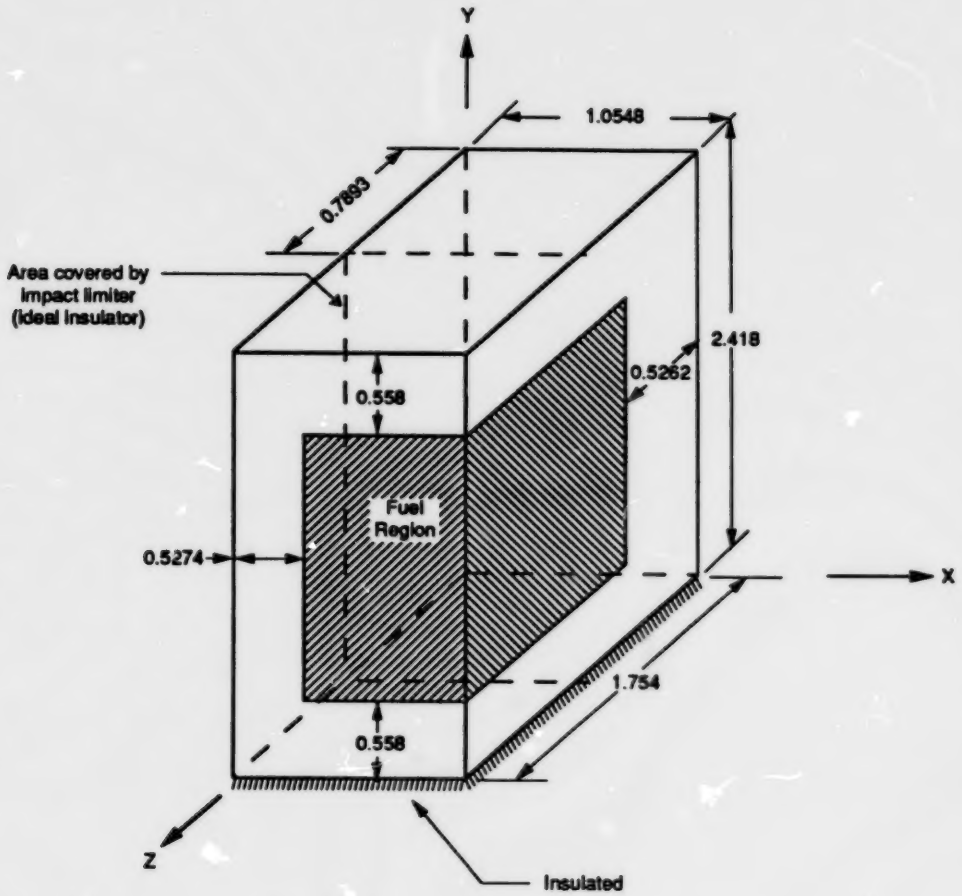


FIGURE 5

COMPARISON BETWEEN EXPERIMENTAL RESULTS /4/ AND PRESENT THEORETICAL RESULTS FOR THE HOTTEST MODULE TUBE TEMPERATURE

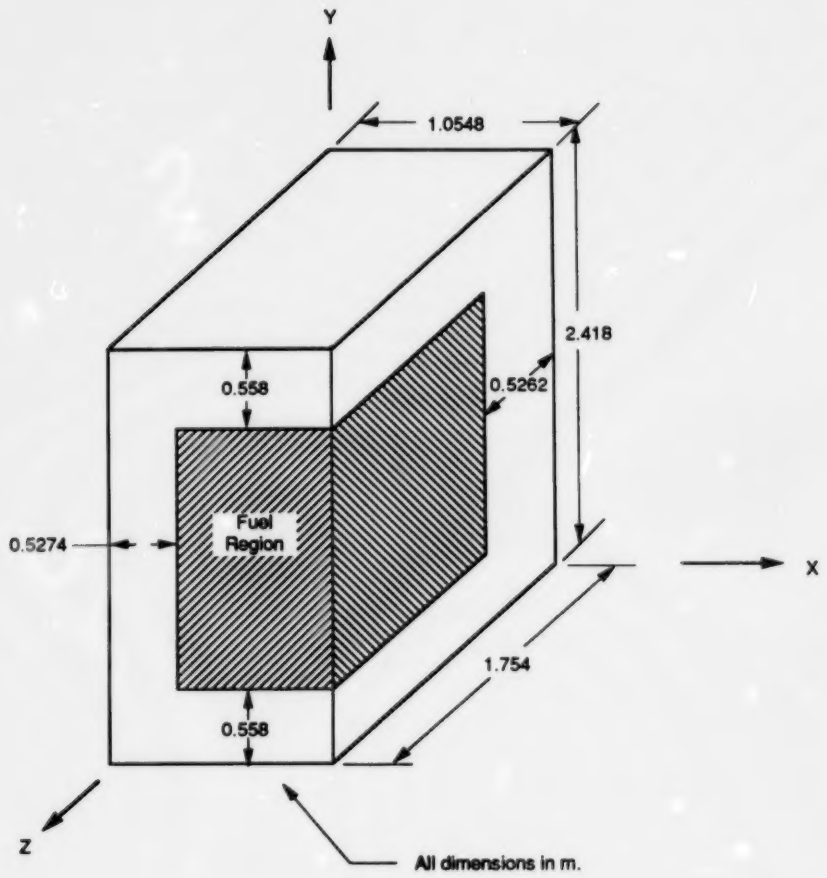


All dimensions in m.

NOTE: Due to symmetry, only 1/4 analyzed.

FIGURE 6

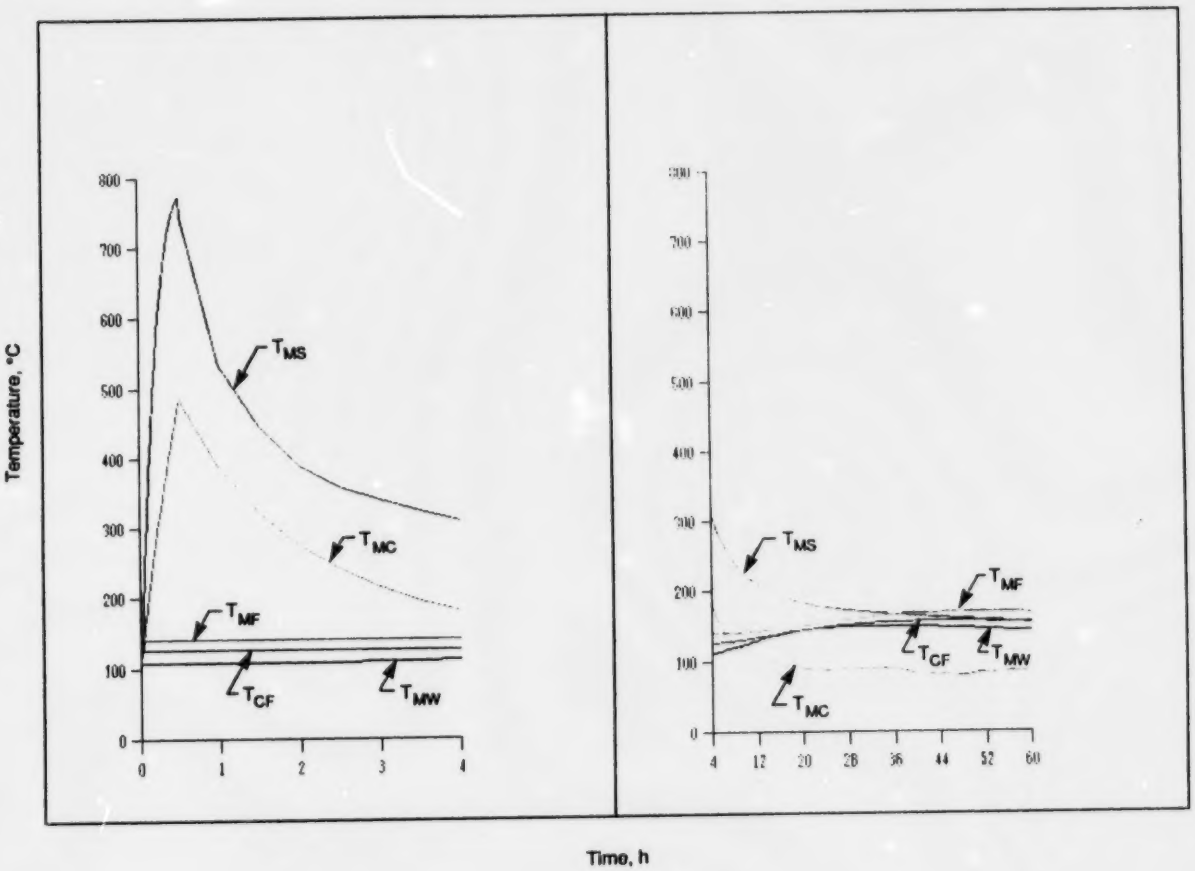
SCHEMATIC DIAGRAM OF MODELLED FULL-SCALE CIC UNDER NORMAL OPERATING CONDITIONS (CIC BOTTOM INSULATED)



NOTE: Due to symmetry, only 1/4 analyzed.
No impact limiter

FIGURE 7

SCHEMATIC DIAGRAM OF MODELLED FULL-SCALE CIC UNDER FIRE ACCIDENT CONDITIONS (CIC FULLY ENGULFED IN FIRE-BOTTOM NOT INSULATED)



T_{MS} = Maximum Outer Surface (Outer Liner-Corners)
T_{MC} = Maximum Outer Surface (Outer Liner-Side Centers)
T_{MW} = Maximum Inner Surface (Inner Liner)
T_{CF} = Average Cavity Fluid
T_{MF} = Maximum Fuel Sheath

FIGURE 8

FIRE ACCIDENT TEMPERATURE RESULTS AT VARIOUS LOCATIONS

TABLE 1
THERMAL PROPERTIES FOR ANALYSIS
OF EXPERIMENTAL HALF-SCALE CIC CAVITY

TEST #	HEAT INPUT (W/BUNDLE)	AIR THERMAL PROPERTIES				
		ρ (Kg/m³)	c (J/Kg.°C)	λ (W/m.°C)	ν (m²/s)	β (1/°C)
0	0.25	1.1666	1005.9	0.264E-1	0.1599E-4	0.3300E-2
1	0.50	1.1343	1006.4	0.271E-1	0.1690E-4	0.3205E-2
2	1.00	1.0733	1007.6	0.284E-1	0.1863E-4	0.3039E-2
3	1.50	1.0231	1008.5	0.294E-1	0.2005E-4	0.2915E-2
4	2.00	0.9865	1009.5	0.304E-1	0.2127E-4	0.2816E-2
5	2.50	0.9565	1010.8	0.313E-1	0.2261E-4	0.2717E-2
6	3.00	0.9241	1012.0	0.323E-1	0.2404E-4	0.2617E-2
7	4.00	0.8786	1014.3	0.338E-1	0.2613E-4	0.2487E-2
8	5.00	0.8409	1016.8	0.351E-1	0.2834E-4	0.2375E-2

ρ = Density

c = Specific Heat

λ = Thermal Conductivity

ν = Kinematic Viscosity

β = Coefficient of Volume Expansion

TABLE 2
WALL TEMPERATURE BOUNDARY CONDITIONS
OBTAINED FROM HALF-SCALE CIC CAVITY /4/

TEST #	HEAT INPUT (W/BUNDLE)	AMBIENT AND WALL TEMPERATURES (°C)				
		T_A	T_1	T_3	T_4	T_5
0	0.25	19.0	23.66	23.50	24.00	23.66
1	0.50	19.0	26.77	26.33	27.83	26.33
2	1.00	18.0	34.11	33.16	35.83	33.33
3	1.50	19.0	40.33	39.33	42.83	39.33
4	2.00	18.0	45.44	44.16	48.50	44.33
5	2.50	20.0	51.66	50.16	55.16	50.33
6	3.00	20.0	57.77	56.00	61.83	56.16
7	4.00	19.0	66.88	64.83	71.83	63.66
8	5.00	19.0	75.00	73.00	81.00	71.50

See Also Figure 4

TABLE 3
THERMAL PROPERTIES - NORMAL

ρ (Kg/m³)	c (J/Kg.°C)	λ (W/m.°C)	ν (m²/s)	β (1/°C)
CIC Wall - High Density Concrete				
3500.0	838.0	2.77	—	—
Fuel Region				
10500.0	280.0	0.03	—	—
Cavity Fluid - Air				
0.96	1009.0	0.03	2.22E-5	2.736E-3

ρ = Density

c = Specific Heat

λ = Thermal Conductivity

ν = Kinematic Viscosity

β = Coefficient of Volume Expansion

TABLE 4A
INSOLATION DATA FOR 12 HOURS

* Ambient Temperature, T_A = 38 °C
Horizontal Surfaces, $\dot{q}_H$ = 800 W/m²
Vertical Surfaces, $\dot{q}_V$ = 200 W/m²

* Also Used in Analysis Without Insolation

TABLE 4B
ADDITIONAL DATA - NORMAL

CIC Exterior Surface Emissivity, ϵ_E = 0.5
CIC Interior Surface Emissivity, ϵ_I = 0.5
Fuel Region Emissivity, ϵ_F = 0.7
Heat Generation, $\dot{Q}_G$ = 751.7 W/m³ (6 W/Bundle)

TABLE 5
SUMMARY OF RESULTS - NORMAL

Temperature & Pressure Results (°C) (kPa)a		No Insolation		With Insolation	
		No IL	With IL	No IL	With IL
Maximum Fuel Sheath,	T_{MF}	118.3	139.8	119.4	141.1
Average Cavity Fluid,	T_{CF}	102.4	125.6	103.6	126.5
Inner Lid (Center),	T_{IL}	84.9	101.4	87.3	103.7
Outer Lid (Center),	T_{OL}	54.8	58.3	91.5	95.8
Average Internal Wall,	T_{IW}	75.6	102.4	76.8	103.2
Average External Wall,	T_{EW}	51.4	82.5	70.2	90.4
Maximum External Vertical Wall, (Center)	T_{MC}	57.0	61.9	65.4	71.7
Maximum External Wall,	T_{MS}	75.4	100.4	97.8	100.4
Maximum Wall,	T_{MW}	84.9	114.0	97.8	114.0
Internal Pressure (Air),	P	129.2	137.2	129.6	137.5

IL = Impact Limiter

TABLE 6
THERMAL PROPERTIES - FIRE

ρ (Kg/m³)	c (J/Kg.°C)	λ (W/m.°C)	ν (m²/s)	β (1/°C)
CIC Wall - High Density Concrete				
3500.0	838.0	2.77	—	—
Fuel Region				
10500.0	280.0	0.03	—	—
Cavity Fluid - Air				
0.96	1009.0	0.03	2.22E-5	2.736E-3

ρ = Density

c = Specific Heat

λ = Thermal Conductivity

ν = Kinematic Viscosity

β = Coefficient of Volume Expansion

TABLE 7A
DATA FOR FIRE ENVIRONMENT

Flame Temperature, T_{FL} = 800 °C
Flame Emissivity, ε_{FL} = 0.9
Vertical Surfaces, α_{S} = 0.8

TABLE 7B
ADDITIONAL DATA - FIRE

CIC Interior Surface Emissivity, ε_{I} = 0.5
Fuel Region Emissivity, ε_{F} = 0.7
Heat Generation, $\dot{Q}_{G}$ = 751.7 W/m³ (6 W/Bundle)

TABLE 8
SUMMARY OF RESULTS - FIRE
(Decay Heat = 6 W/Bundle)

Temperature & Pressure Results (°C) (kPa)a			* Time (s)
Maximum Fuel Sheath,	T_{MF}	168.9	169,200
Average Cavity Fluid,	T_{CF}	156.6	160,200
Inner Lid (Center),	T_{IL}	131.0	88,200
Outer Lid (Center),	T_{OL}	463.4	1,800
Average Internal Wall,	T_{IW}	134.6	95,400
Average External Wall,	T_{EW}	518.6	1,800
Maximum Outer Surface (Center),	T_{MC}	485.6	1,800
Maximum Outer Surface,	T_{MS}	771.1	1,800
Maximum Inner Surface,	T_{MW}	149.6	120,600
Internal Pressure (Air),	P	148.0	160,200

* Time measured from the start of fire

Fire Duration = 1,800 s (0.5 h)
Cooldown Period = 216,000 s (60.0 h)